X-ray Spectroscopy of Low-Mass X-ray Binaries

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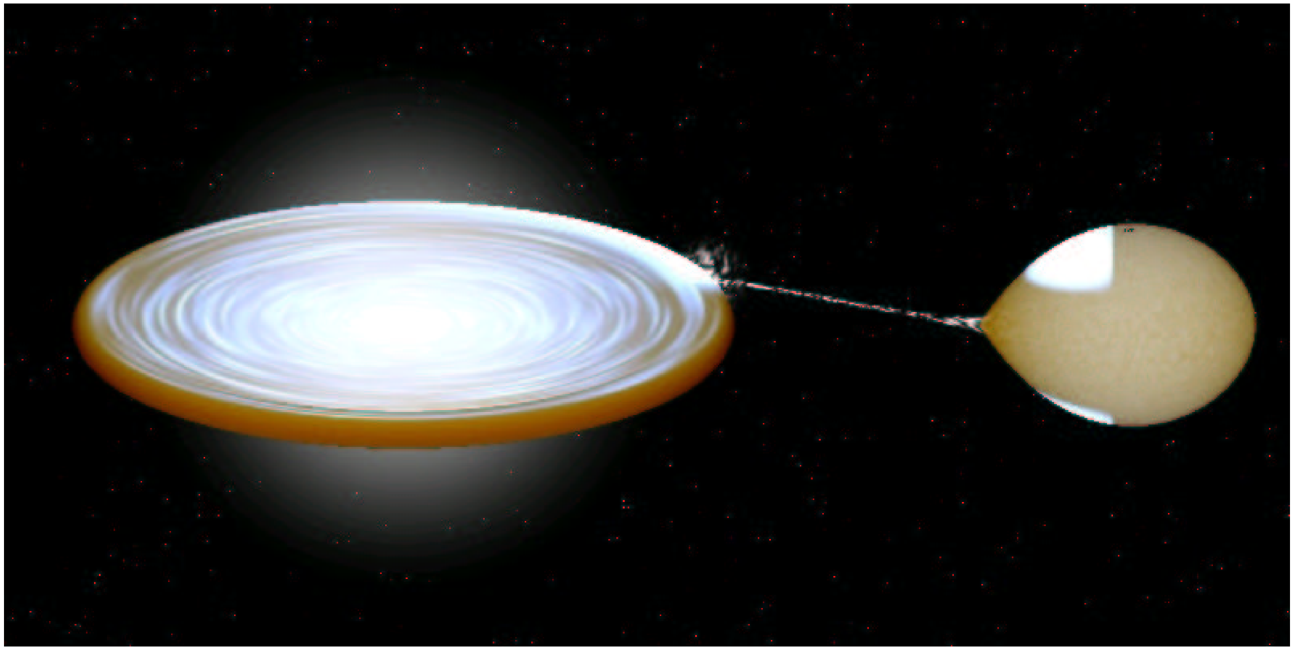
Outline

- Ultracompact LMXBs
  - What are Ultracompact binaries and why are they interesting?
  - Evidence for C-O white dwarf donors.
  - Caveats/Weak Points.

- Interstellar Medium
  - Introduction to the ISM.
  - Motivation.
  - Determining the Model.
  - Identification of Absorption Features.
  - Studying the ISM.

Low-Mass X-ray Binaries



(Created using BinSim by R. Hynes)

Neutron Star or Black Hole + Companion of $\lesssim 1\ M_\odot$

$\sim$150 in the Galaxy with Orbital Periods: 11 min – 100s days

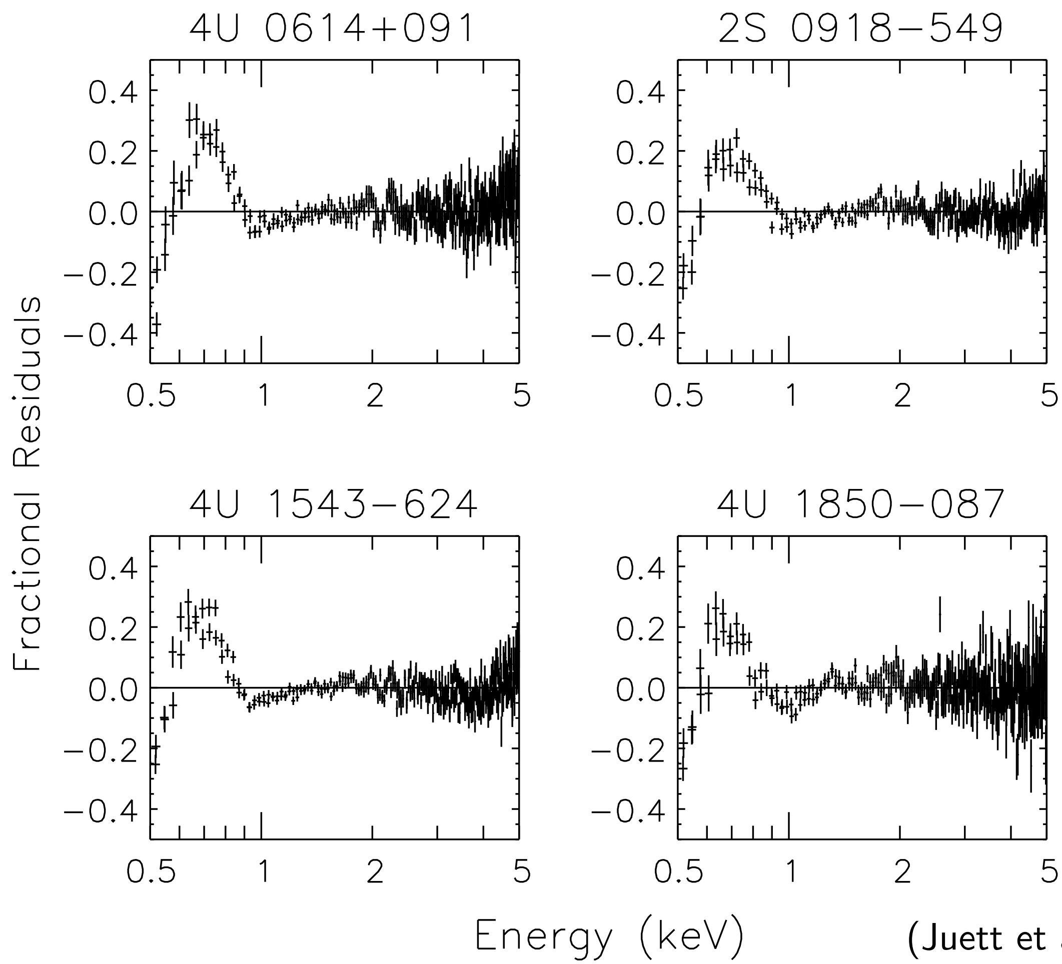
Mass Transfer Primarily Through Roche Lobe Overflow

Most have Featureless X-ray Continuum Emission

Ultracompact Binaries

- $P_{\rm orb} \lesssim 80$ min
  - Require Hydrogen-deficient or degenerate companions
- 8 ultracompact LMXBs (out of 52 with $P_{\rm orb}$)
- 3 of 5 X-ray Millisecond Pulsars
- 2 of 5 Globular Cluster binaries with $P_{\rm orb}$
- $\approx$8 additional candidate UC binaries with low $L_{\rm opt}/L_{\rm X}$
  (van Paradijs & McClintock 1994)
- All but 1 of the known and all of the candidate UC binaries have confirmed NS primaries.

ASCA spectra of 4 LMXBs

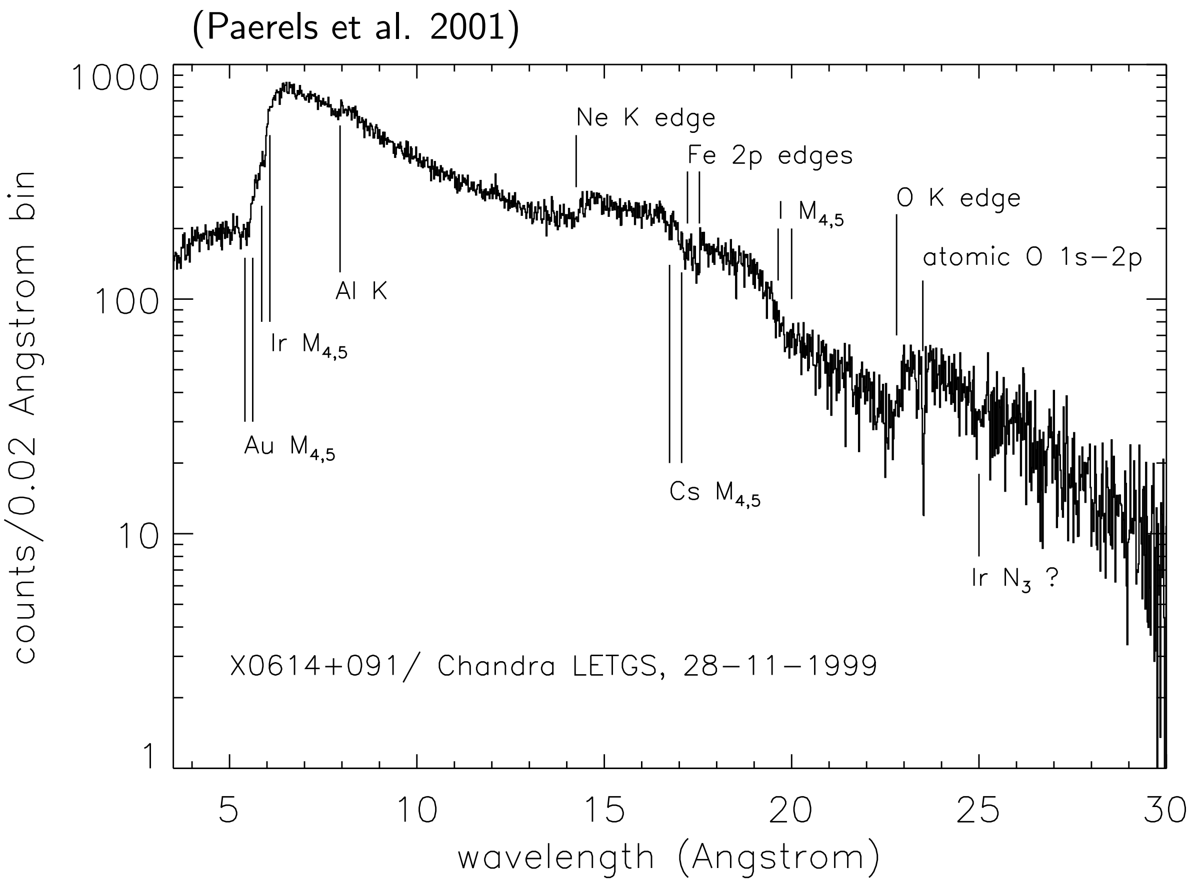


(Juett et al. 2001)

Residuals from absorbed PL + BB model

Feature at 0.7 keV previously attributed to unresolved Fe/O emission lines

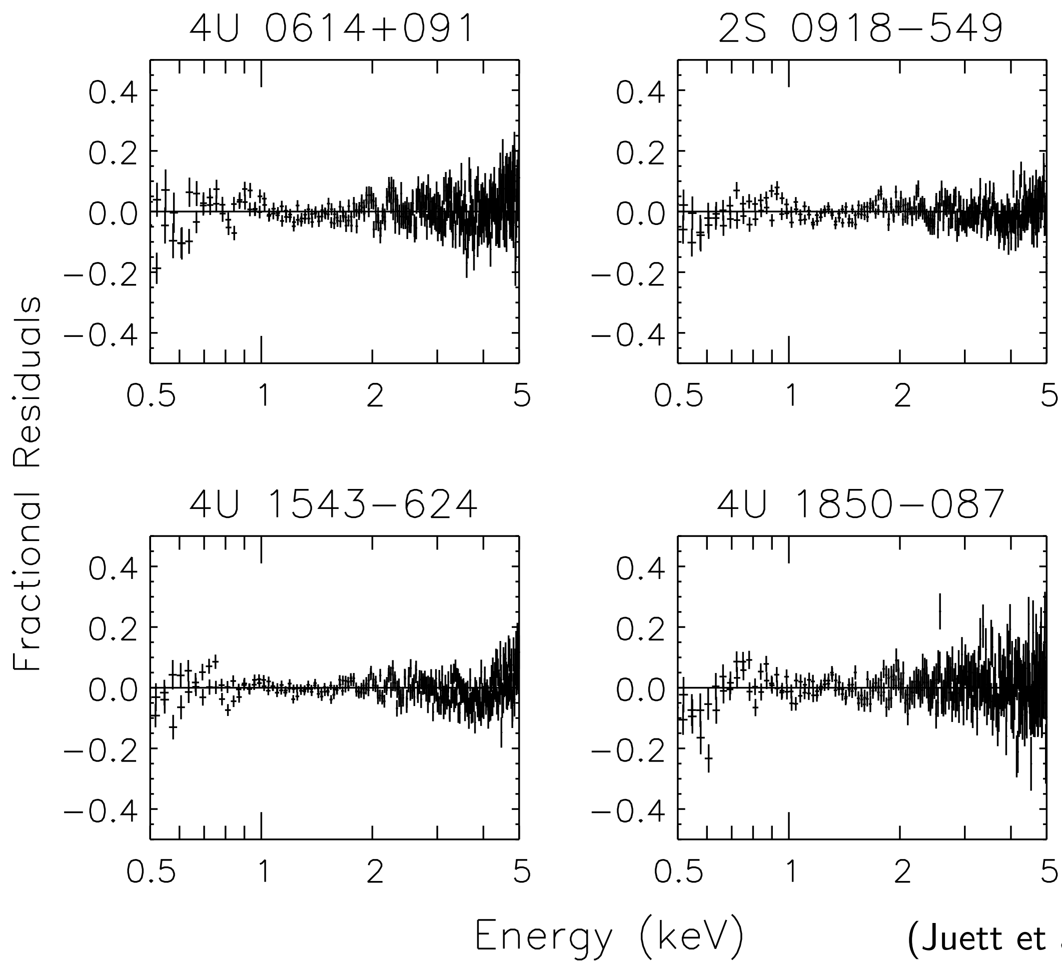
Chandra spectrum of 4U 0614+091



No emission lines

Ne/O ratio ≈ 1.25 (Ne/O in ISM $= 0.18$)

Alternative explanation for the 0.7 keV feature



(Juett et al. 2001)

Variable O and Ne absorption

Ne/O ratios 0.9–1.1 (Ne/O in ISM $= 0.18$)

Summary of 4U 1626−67 Results

- Ultracompact binary with $P_{\rm orb} = 42$ min.
- Oxygen and Neon emission lines found.
  (Angelini et al. 1995; Schulz et al. 2001)
- Emission lines resolved into Doppler shifted pairs with *Chandra*.
  (Schulz et al. 2001)
- Absorption edges from *Chandra* spectrum suggest local absorption with Ne/O ratio = 0.22.
  — much larger than expected for He WD.

Schulz et al. suggested that donor was the chemically fractionated core of a C-O or O-Ne-Mg white dwarf.

Interpretation of Unusual Ne/O ratio

4U 1850−087 is also ultracompact binary with $P_{\rm orb} = 21$ min.

No orbital periods found for 4U 0614+091, 2S 0918−549, or 4U 1543−624.

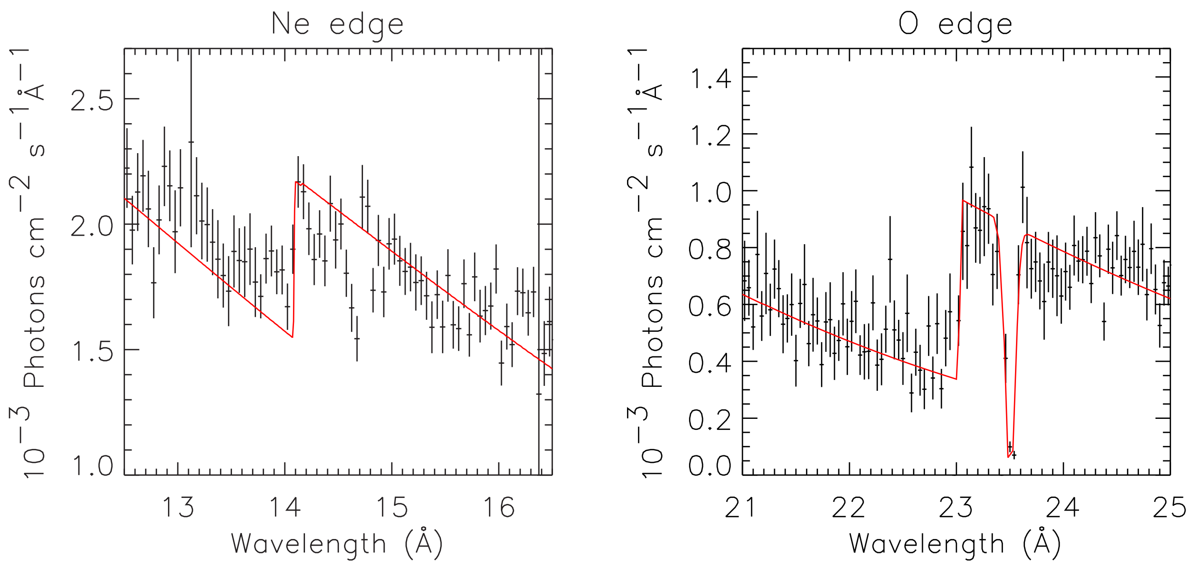
All four sources have low $L_{\rm opt}/L_{\rm X}$ suggestive of ultracompact nature.

We suggested that all four sources were ultracompact and had Ne-rich donors similar to 4U 1626−67.

Grating Spectra of 2S 0918−549

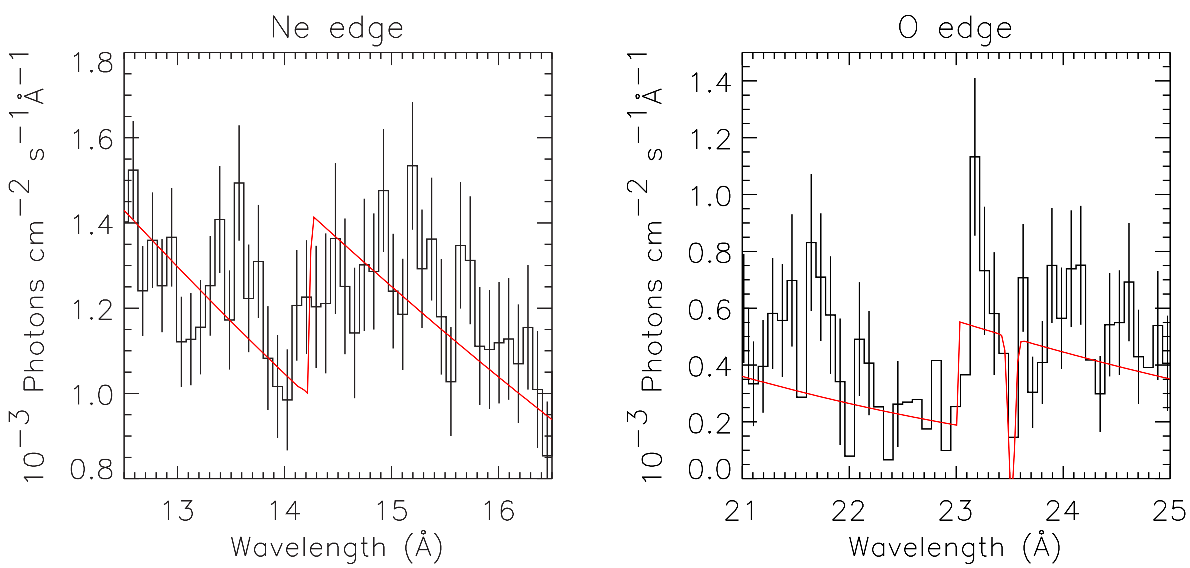
RGS

Ne/O ratio 0.46±0.03



HETG

Ne/O ratio 0.52±0.12



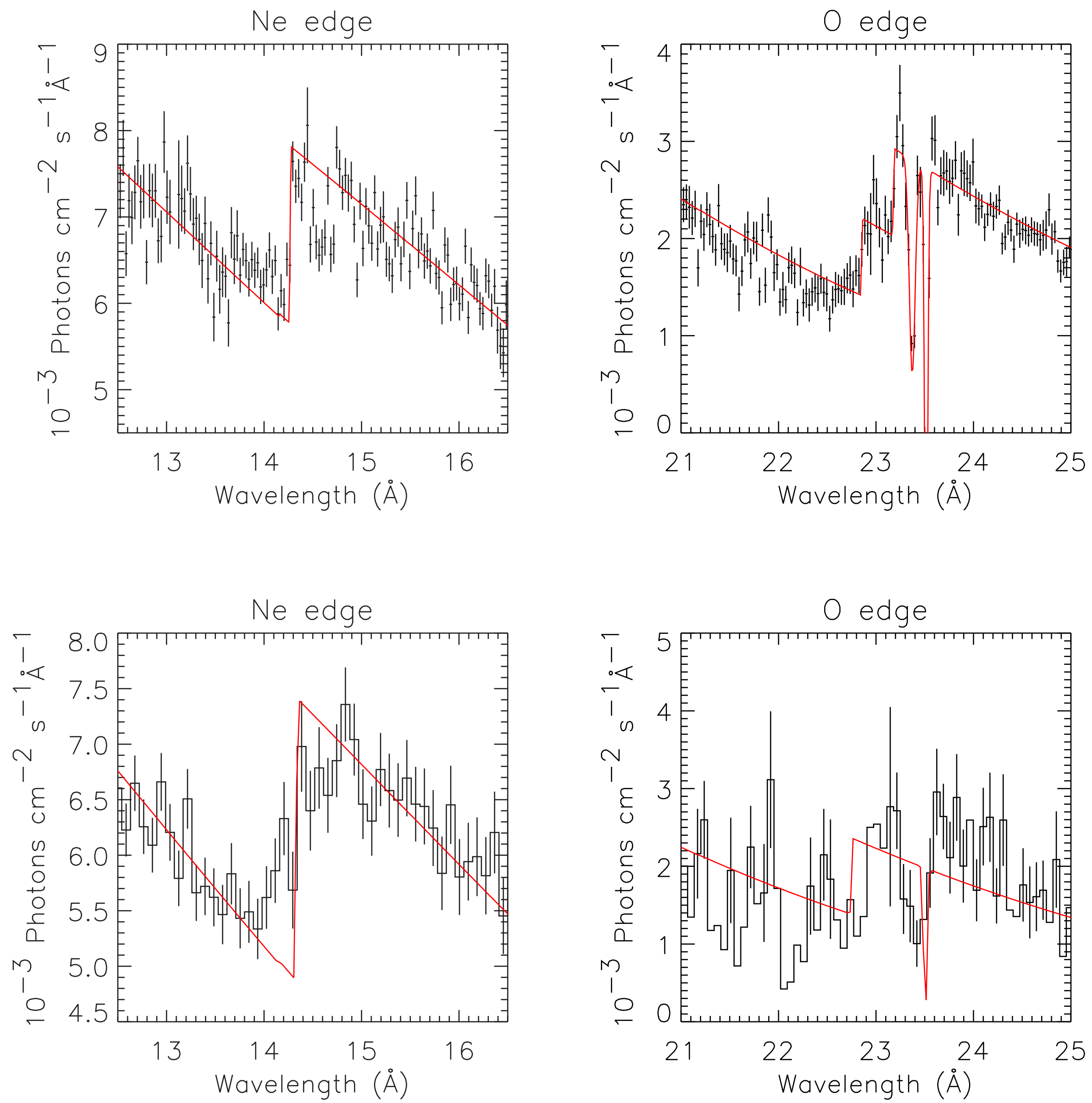
Grating Spectra of 4U 1543−624

RGS

Ne/O ratio 0.54±0.03

HETG

Ne/O ratio 1.5±0.3



What do *Chandra* and *XMM* results mean?

Results confirm unusual Ne/O ratio, pointing to Ne-rich local material.

Variations in the ratio also strengthen suggestion that local material is present.

But variations seem to have relationship to broadband spectral properties of the source — ionization may be important.

Therefore, measured ratio not likely to be indicative of abundance of the local absorbing material.

Caveats/Weak Points

- Is the material local?
  No X-ray emission lines for most of the sources.

- ISM Properties

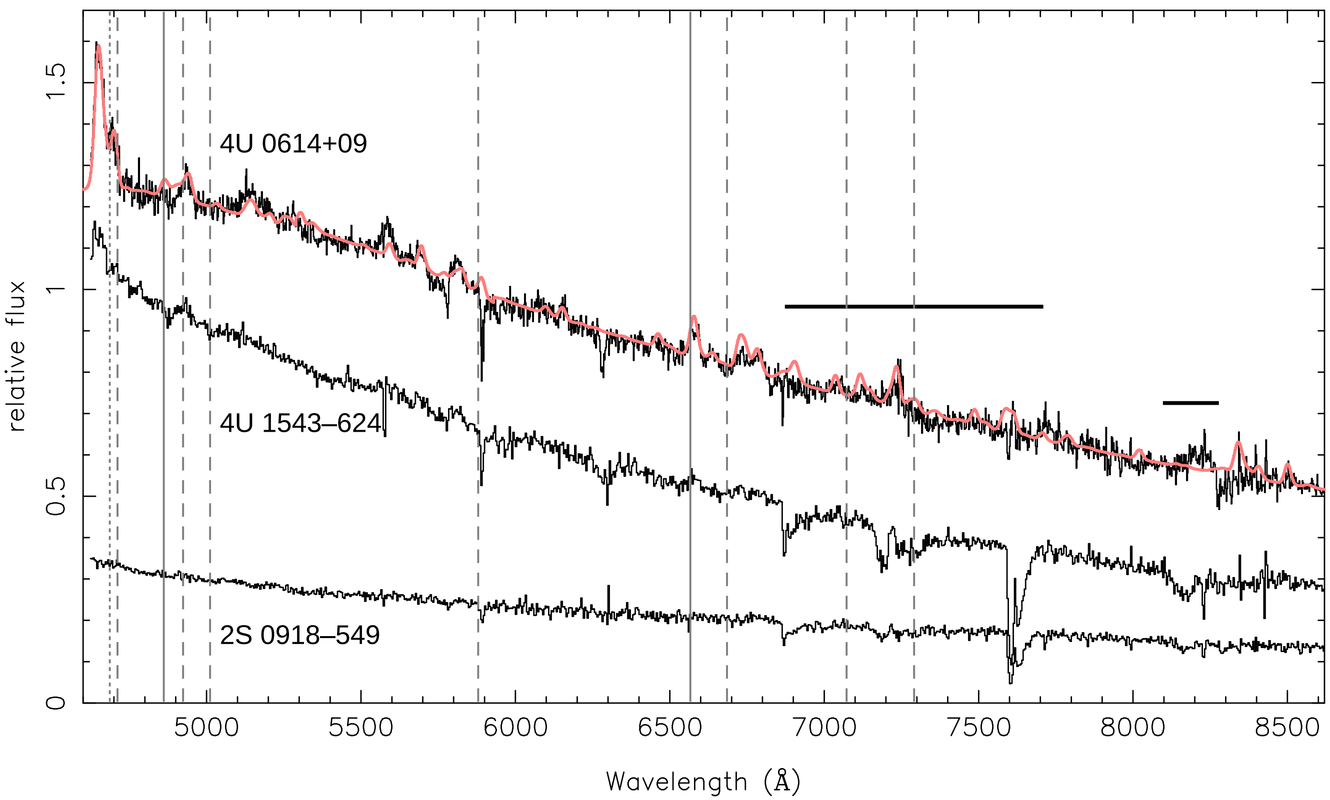
  – Neon abundance not well known.
  – Effect of dust grains or molecular species on derived abundances.

- Shape of Neon edge.
  Does this imply anything about the properties of the Neon?

- Ionization effects.
  How does local ionization of the material affect derived abundances?

Optical Results of Neon-Rich Sources

Nelemans et al. 2003



No Hydrogen or Helium emission lines seen

Only Carbon and Oxygen lines identified

4U 1543$-$624: $P_{\rm orb} = 18$ min. (Wang & Chakrabarty 2004)

Summary of UC Results

4U 1626−67

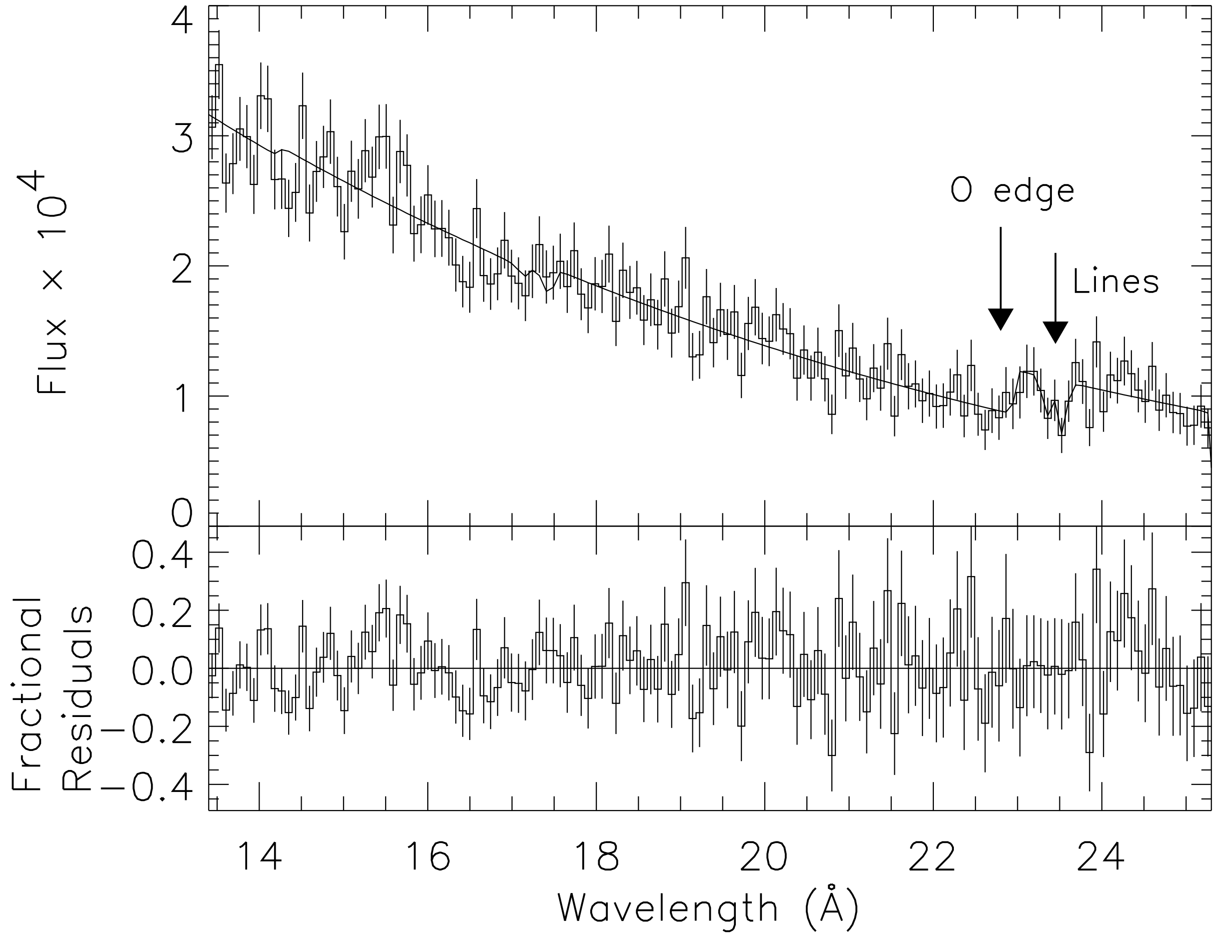
- Ne & O lines & absorption detected
- Point to C-O WD donor
- Optical/UV spectra back this up

Other sources

- *ASCA* spectra explained by high Ne/O
- High-resolution spectral evidence ?
- Optical spectra similar to 4U 1626−67

Not all UC Binaries have to be Ne-rich

XTE J0929−314, Juett, Galloway, & Chakrabarty 2003



Absorption consistent with interstellar origin

The Interstellar Medium

Contains Gas and Dust in both Diffuse Medium and Compact Clumps.

Diffuse Phases: Cold Neutral, Warm Neutral, Warm Ionized, & Hot Ionized

Emission Line Studies

- Radio studies: Hydrogen 21 cm, CO.
- Probe through the galaxy.

Absorption Line Studies

- Ultraviolet and Optical.
- Probe line of sight to source.
- Limited number of elements/ionization states.
- Limited in distance: $d \lesssim 2$ kpc.

Using X-ray Absorption Features

- Can probe to larger distances.
- Bandpass includes K-shell transitions of all elements from C to Fe.
- All ionization states available.
- Limited only by the strength of the features or sensitivity of the instrument.

Use X-ray binaries as sources. They are the brightest X-ray objects.

Motivation

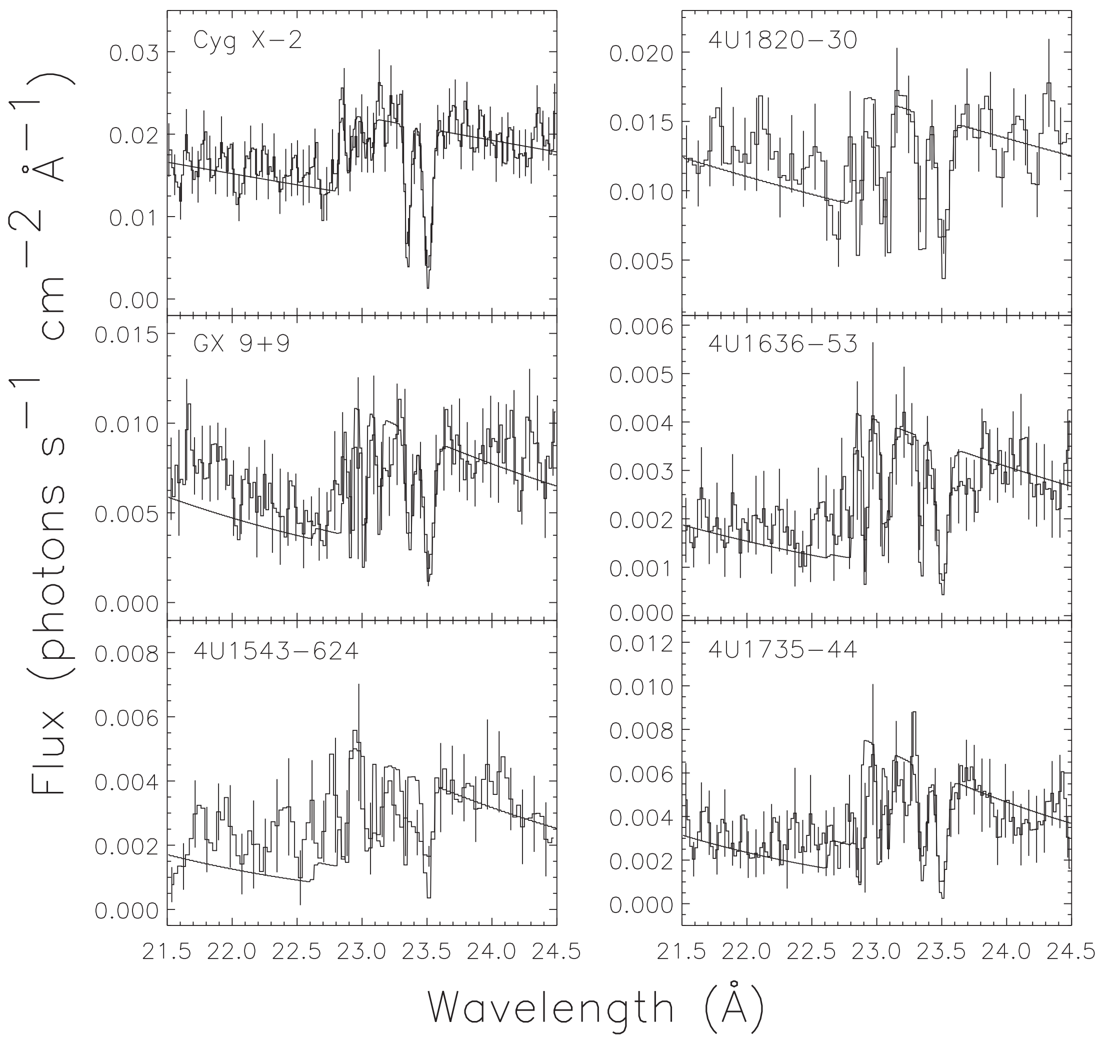
Four studies of O edge have found different results (Paerels et al. 2001, Schulz et al. 2002, Takei et al. 2002, de Vries et al. 2003).

- Found 1–3 edges with positions from 22.58–23.13 Å.
- Found 1–2 absorption lines.
- All identified O I 1s-2p absorption line.

Standard absorption models (tbabs, phabs, wabs) do not have resolution comparable to the gratings on *Chandra* and *XMM*.

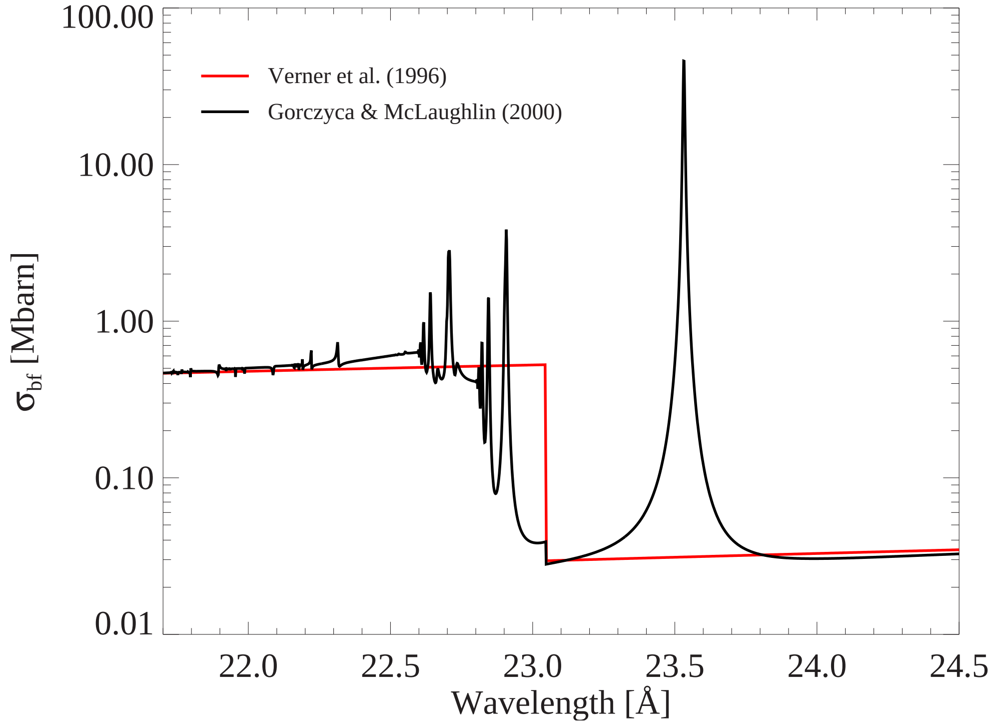
- Accurate absorption model necessary to understand source spectral properties

Modeling HETGS Spectra



- HETG: $\Delta\lambda = 0.023$ Å, highest resolution.
- Fit spectra of 7 X-ray sources.
- Used high-S/N data as template.
- Model includes 2 absorption edges and 5 Gaussian absorption lines.

Comparing Cross-Sections

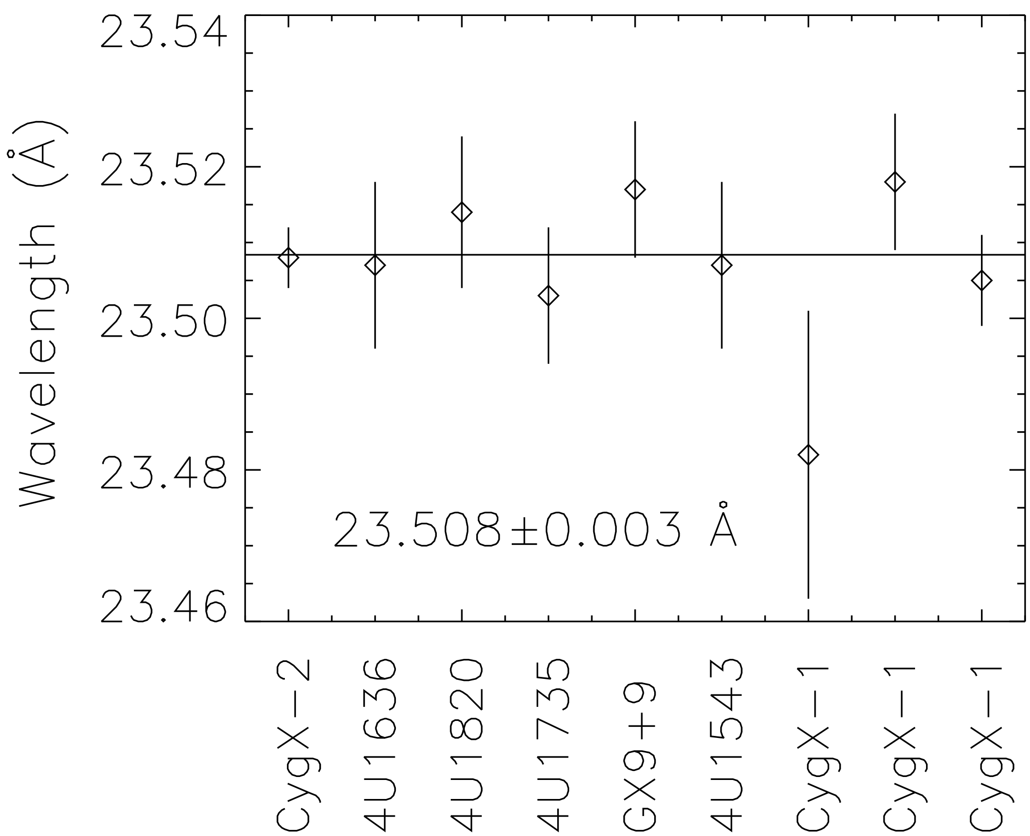


- Old models no longer appropriate.
- New instruments can resolve structure in neutral O absorption.
- Expect features from ionized O as well.

Compared data with theoretical predictions from neutral and ionized O (Gorczyca & McLaughlin 2000, Pradhan et al. 2003).

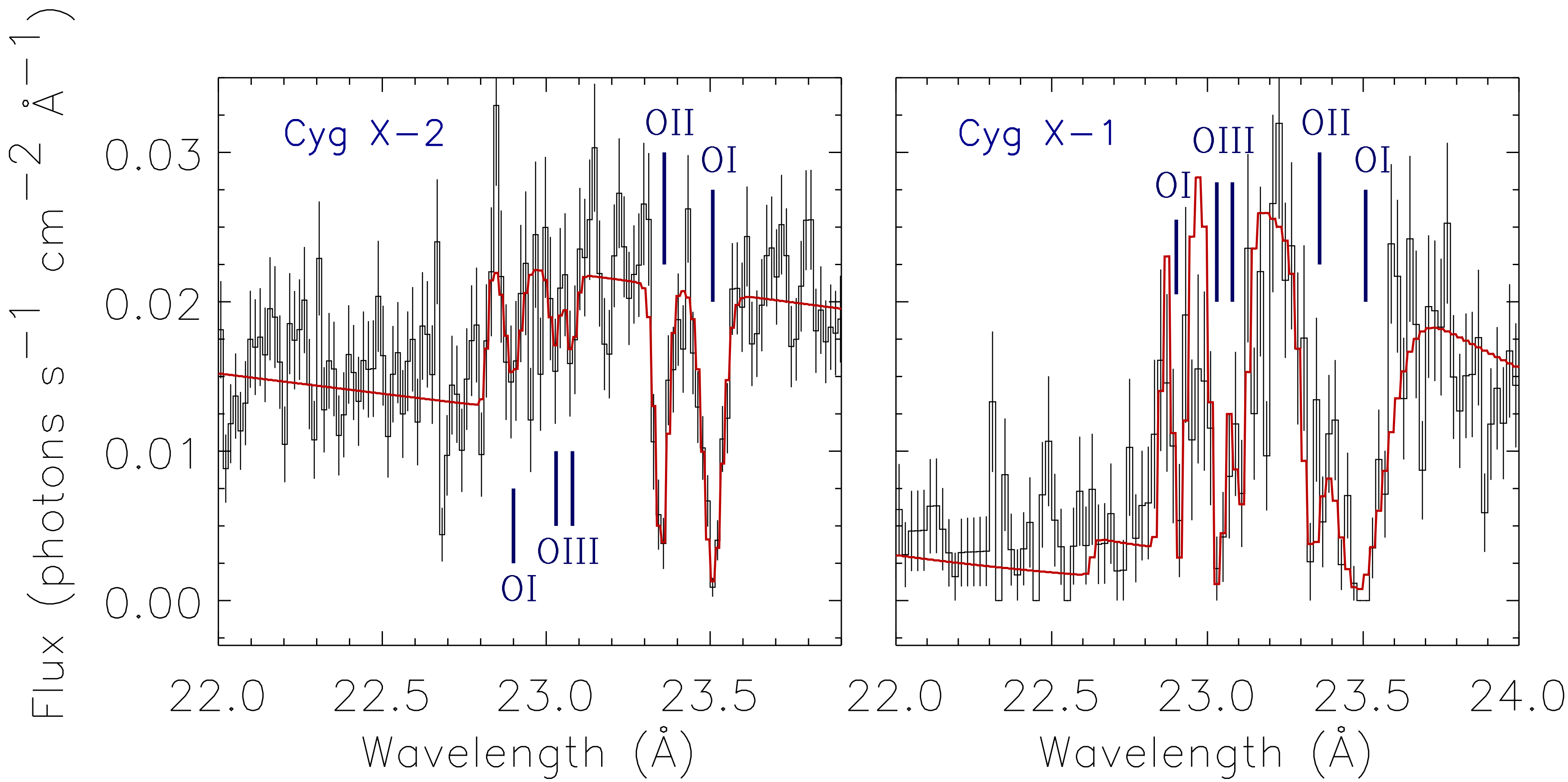
Used O I 1s-2p absorption line as benchmark.

O I 1s-2p Line Positions



More accurate measurement of the position of this line than done in laboratory.

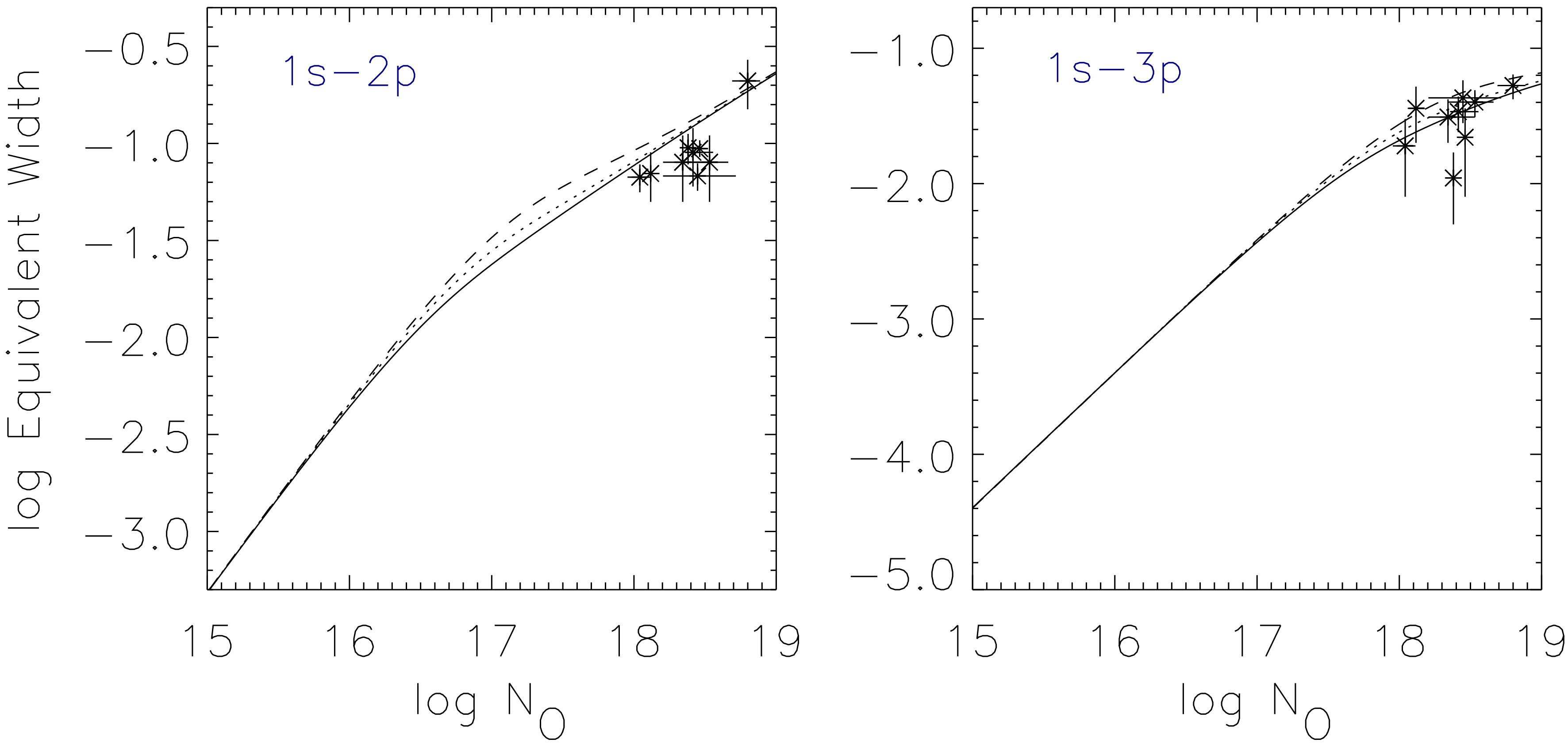
Identified Lines



Identified only neutral and ionized O features.

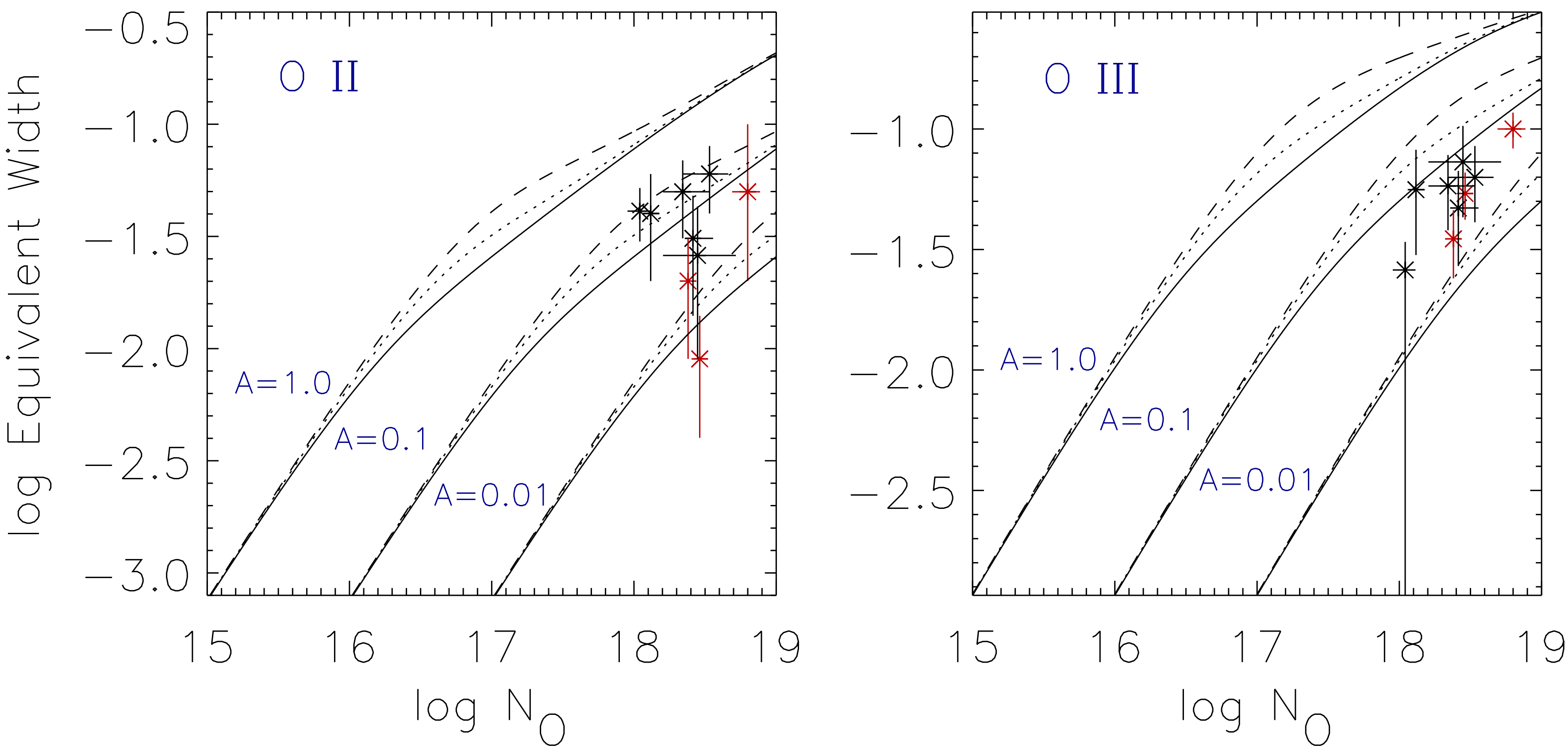
Column density measurements calculated at wavelength away from edge structure.

Curve of Growth — Neutral O



Data consistent with the low velocity dispersions found in other studies.

Curve of Growth — Ionized O



$A = N_{\rm ionized}/N_{\rm neutral}$

First measurement of large-scale ionization fraction in ISM.

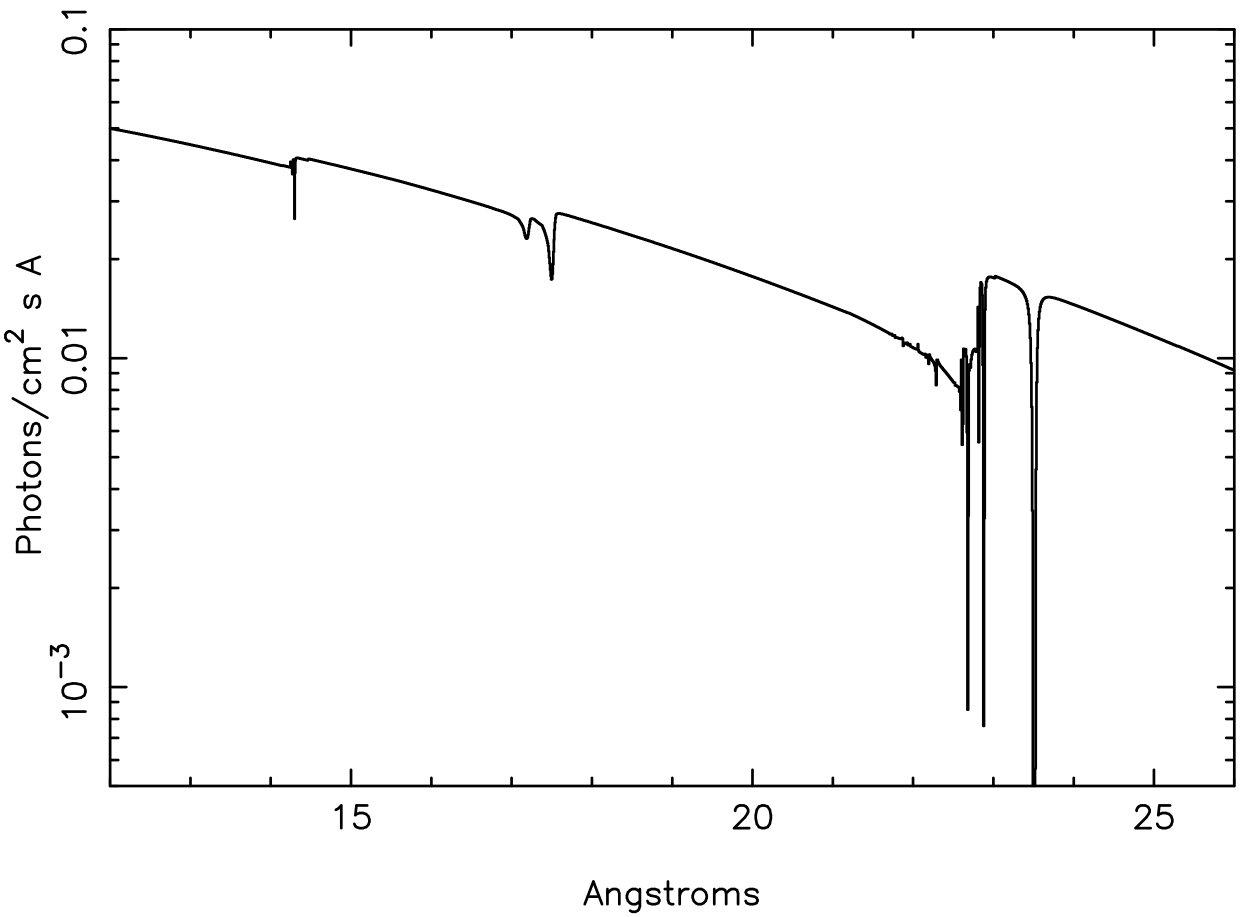
Other Issues

- Instrumental Contribution
  - Instrumental absorption feature at 23.33 Å included in model of contaminant.
- Oxygen in Molecules/Dust
  - Place limits on amount of O in other forms: 10–40%.
  - Consistent with other determinations (Andrè et al. 2003).
- Local vs. ISM
  - Correlation between neutral column density and ionized EW suggests that to first order ionized lines are from ISM.
  - But some evidence for material local to the binary in Cyg X-1.

Future Work

- Sco X-1 — high S/N observation
- Other elements — Fe, Ne, Mg, Si
- Expand range of $N_{\rm O}$ — e.g., AGN
- Future Missions: Astro-E2, Constellation-X

Updating the Absorption Model



Added oxygen, neon, and iron theoretical cross-sections to `tbabs` model.

Testing/comparison to grating spectra underway.

Conclusions

Oxygen edges of X-ray binaries are well described by a model that includes neutral and ionized O features.

Velocity dispersions consistent with other measurements: $\lesssim 200$ km s^{-1}.

Made the first measurements of the large-scale O II and O III abundance, relative to O I.

- O II/O I ≈ 0.1, O III/O I $\lesssim 0.1$.

- Roughly consistent with expectations given H II/H I$\approx 1/3$.